THE GEOPHYSICAL EXPRESSION OF SELECTED MINERAL DEPOSIT MODELS

Introduction to Geophysical Deposit Models

by

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INTRODUCTION

The use of formal mineral deposit models in the assessment of mineral resources on public lands has been established for almost 10 years within the U.S. Geological Survey. A catalogue of deposit models developed for assessment purposes was published in 1986 (Cox and Singer, 1986) and a supplemental catalogue appeared in 1991 (Orris and Bliss, 1991). Both of these catalogues succinctly summarize the geologic and to a lesser extent the geochemical signatures of the deposits, but give virtually nothing regarding the geophysical expression of the deposits. Thus the geophysicist assigned to an assessment team had to rely on his experience in order to interpret the significance of available geophysical data to the potential for various types of deposits in the area of study. This procedure presented problems in making full use of available data because of inexperience of some staff, lack of familiarity with all deposit types under consideration, and incomplete understanding of the varieties of geophysical data being used. It was also recognized that geophysical data needed to play a greater roll in the assessment process where relevant geologic data were obscured by barren cover rocks.

Information used to assess covered areas is obtained by extrapolation from outcrop, from secondary effects such as dispersion haloes that may be identified by geochemical or geophysical techniques, or by direct measurement of some physical property or property contrast at depth by geophysical methods. Thus, the applicability of geophysical data to assessment and exploration becomes increasingly important as the focus changes to covered deposits.

To better meet the needs of USGS staff for basic information on the geophysical signatures of the various deposit models of Cox and Singer (1986) an effort was initiated to compile a preliminary description of the geophysical characteristics of their 85 original models. The geophysical models that follow are interim compilations intended to be descriptive in nature, as the Cox and Singer models are, and to be relatively free from genetic constraints. We hope that this compilation, by being descriptive in nature, will be found useful even if current ideas on the genesis of some deposit types may change.

This paper is divided into two main parts, an extensive introduction, and a catalogue of geophysical models. The introduction explains the rational for, and format of the models, provides a brief review of geophysical methods, and gives numerous tables and graphs showing values and ranges of physical properties of host and cover rocks. By summarizing host and cover rock properties in the introduction, model compilers do not have to address host rock properties or property contrasts between various host rocks and the deposit when preparing a model. A catalogue of models follows the introductory material, each model being prepared by different staff of the Branch of Geophysics.

This compilation is, of necessity, preliminary because most deposit types have not had complete geophysical descriptions given in published literature, or relatively little public information of any kind is available on which to base a geophysical description. When trying to define the averages and ranges of physical properties of individual deposit types, the limitations of public information become even clearer. However, a start needs to be made, and if it contributes nothing else, it will identify areas of weakness in our data base. This we hope will be a challenge to other users, to make corrections where errors occur, but more importantly to augment the data base with their own hard data.

In looking over the geophysical literature we find that there are numerous papers that review the geophysical characteristics of a particular deposit, but very few that try to summarize results for a particular deposit type. But, it is the summary papers that provide the synoptic view on which to base a model description. Excellent examples of such papers are those of Kamara (1981) or Macnae (1979) on diamond-bearing kimberlites. Papers such as these on all the various deposit types would be desirable, but are not likely to appear in the near future. The compilation presented here is intended to provide interim guidance on the geophysical characteristics of deposits until adequate review papers are prepared, as well as to provide sufficient literature references to ease the search for the person needing further information.

Descriptions of deposit geophysical characteristics tend to focus on large scale, deposit-size, property variations, especially in Western literature, with progressively lesser emphasis given to district or regional characteristics. In part this approach reflects the territorial divisions between government and the private sector, the government generally having responsibility for providing basic regional data, and the private sector having responsibility for resource development. This dichotomy in scale has tended to place emphasis in the Western literature on direct deposit expression, with regional or district scale attributes generally passed over in discussions of deposit signatures. Yet it is the regional and district scale attributes of deposits that are important in most government resource assessments. In the former USSR, on the other hand, assessment and exploration have been done by the state, and regional geophysical investigations of the entire crust play a more direct part in regionalization of areas favorable for mineralization (Brodovoi and others, 1970; Zietz and others, 1976; Kuzvart and Böhmer, 1986) than is evident from Western literature. Brodovoi and others (1970) note that in Kazakhstan the use of deep seismic, gravity, aeromagnetic and deep electrical data for mapping the depth to and thickness of major crustal units; depth to the Mohorovicic discontinuity; location, size and type of intrusive rocks; and major crustal structures are used as aids in defining metallogenic regions. Zietz and others (1976) state that in the southeast part of the USSR, tin is associated with a thick crust, lead and zinc deposits correlate with intermediate crustal thickness, while copper and gold are found in areas of thin crust. Our compilations attempt to include regional characteristics, but in many cases information is not directly available.

In attempting to compile the geophysical characteristics of a wide variety of ore deposits, we find that two distinct approaches are possible. One is to focus on individual geophysical techniques and the types of geological problems that may be addressed by each. Deposit types are then related to geophysical methods by identification with particular geologic attributes of a deposit, i.e., are there magnetic minerals in the deposit, or is the deposit fault-controlled? In this approach, it is hard for the compiler to specify, or the user to know, what types of methods may have been used on a particular type of deposit, or what methods are more commonly used.

Another approach is to focus on the deposit type, and identify geophysical characteristics known for that deposit and methods that have been applied. A somewhat similar method has been given by Vakhromeyev and Baryshev

(1984). In this approach, the user has all the attributes of a particular model conveniently at hand. This latter method has been used in this compilation, because assessment and exploration address one, or few, deposit types at a time making it desirable to have a summary of all characteristics of each deposit type in one place rather than scattered throughout a text. This method also ties geophysical models directly to Cox and Singer (1986), focusing on the models rather than the geophysical technique, and as such this compilation is intended to be used as a companion text.

Many authors have unselfishly contributed to this compilation of geophysical signatures of ore deposit models. For each model, the compilers are identified adjacent to the title of the model. Whenever practical, we request that when reference is made to particular models, the individuals who compiled the models be cited, rather than referencing this entire report.

ACKNOWLEDGMENTS

A compilation such as this could not be made without the support and encouragement of co-workers and colleagues both within and outside Government service. We especially want to thank Dave Campbell, Mike Foose, Andy Griscom, Bill Hanna, Bill Hasbrouck, Dan Knepper, and Jim Pitkin, all with the USGS, for their support and assistance in review of this work. From outside government Jack Corbett and Frank Fritz reviewed the material and contributed many useful suggestions and much information. The earlier work of Ed Ballantine on his Doctoral thesis also needs to be acknowledged as providing a substantial data base from which to start building the models.

FORMAT OF THE MODELS

The model descriptions give first the title, compilers, and geophysically similar models followed by nine principal headings: A, geologic setting; B, geophysical definition of the geologic environment; C, geophysical definition of the deposit; D, shape and size of deposit, and any alteration halo and/or cap; E, a physical property table for the deposit, alteration halo, cap, and host rock if appropriate; F, remote sensing characteristics; G, general comments; H, reference list; I, selected illustrations. A few comments are necessary on each of these divisions.

The title section identifies the Cox and Singer (1986) model or models, model number, the compilers, and geophysically similar models. Identification of geophysically similar models is important because it calls attention to models with similar characteristics that the geophysicist should be aware of for assessment or exploration work. By identifying models that are geophysically similar, the compiler does not imply that there is any genetic similarity. He only means to identify other models that he believes have a sufficient number of similar attributes that they need to be considered when evaluating geophysical data.

In some cases compilers have lumped several related Cox and Singer models into one geophysical model because of the similarity of geophysical signatures and/or because of a lack of information on which to separate the deposits geophysically.

The geologic setting, heading A, is intended to be a succinct statement to remind the user of the nature of the Cox and Singer (1986) model. The geophysical models are intended to complement those of Cox and Singer. Users are referred to Cox and Singer (1988) for more details of the geologic setting.

The geophysical definition of the geologic environment, heading B, briefly states the regional- or district-scale geophysical characteristics associated with the deposit. These are features that have been suggested in the literature as important for localizing the particular deposit type. Most relate to small scale structural and lithologic features that define permissible terrains but are rarely deposit specific.

Deposit definition, heading C, briefly states the geophysical attributes of the deposit as described in the literature, and the geophysical methods most used. This section is quite variable in content. Some deposit types provide direct geophysical evidence of mineralization, but many only provide indirect evidence. The compilers provide a summary of exploration experience from the literature which can be highly variable in quality and amount of data. For example, the geophysical literature on porphyry copper deposits (model 17) is extensive, but that for Olympic Dam (Cu-U-Au, model 29b) *or* Kipushi (Cu-Pb-Zn) deposits (model 32c) is quite scarce. The compilers may comment on the potential for a particular geophysical method that, from the literature, had not been tried. A geophysical method not referred to may imply that the method was never tried. However, it also could be due to there being little chance for success of the method, that it would probably not be cost effective, or that it was tried and not found useful. Too often, only successful efforts are reported and the unsuccessful ignored. The user of this model compilation needs to keep in mind the caution flag raised by absence of some methods, but also needs to keep an open mind for the overlooked opportunity.

The next two headings (D size and shape, and E physical properties) provide, to the extent possible, hard data so that modeling of a deposit may be done using a variety of host rock and overburden. These are the quantitative parameters of what Vakhromeyev and Baryshev (1984) call the physico-geological model of an ore deposit. The size of the deposit, its alteration halo and cap, if important, are given. Where grade/tonnage data are available from Cox and Singer (1986) the deposit volume is given for the 90th, 50th and 10th percentiles of deposits, using the average deposit density from heading E. The generalized shape for the deposit, halo and cap are also given for input to a modeling program as appropriate.

Specific physical properties listed in the table (division E) include density, porosity, magnetic susceptibility, magnetic remanence, electrical resistivity, induced polarization (IP) effect, seismic velocity, radioactive element (Radioelement) (K, U, Th) content, and an “others” category. These properties are listed separately for the deposit, any alteration halo, secondary cap, and host rock if appropriate. By breaking down the deposit and its host environment in this way, the geophysicist is able to calculate the response of a deposit in almost any setting with or without alteration products, and for any kind of cover, at least for those properties where specific property values can be assigned. For many of the geophysical responses of ore bodies it is the physical property contrast that is important, rather than absolute values of properties. However, since host and cover rocks may vary significantly it is not practical to list physical property contrasts in this table. This has tended to limit our ability to identify quantitative values for a number of properties. However, for those wishing to compute model responses, the reference list should provide supplemental information.

Where a numeric value is assigned in the table or numeric ranges are given, superscript numbers refer to the references from which the data were obtained. Units for the various physical properties may vary among models reflecting what was available in the literature. This is a particular problem for electrical induced polarization (IP) measurements which are reported in various ways that are not dimensionally consistent. A problem also exists for gamma-ray spectrometry for Radioelement concentrations, as too few systems are calibrated so that only counts-per-second are often reported. For such cases the compiler decides how best to present the results.

For many entries in the table reliable quantitative values are not available. For these cases, when sufficient literature information is available to make an informed qualitative estimate, the compiler will insert high, medium, low, variable, etc., as a best estimate. If this qualitative estimate is suspect, the qualitative term will have a question mark following it such as (high?). If the compiler feels there is insufficient information on which to even hazard a guess, then the entry will be a question mark (?). Properties of the host rock are given in the table only if a particular host rock is unique to the deposit, or as for Olympic Dam (29b) for which there is only one example. Where the deposit may be hosted by a variety of rock types an asterisk (*) is shown, indicating that the properties for any particular host should be obtained from tables that follow in this introduction. Properties for overburden will also be found in these tables. In some cases the property headings of deposit, alteration halo, cap, and host rock, have been changed because of the way that geophysics is applied to particular deposit types, and because of limitations of literature information.

For example, in the case of carbonatites the deposit, alteration halo, cap, and host categories were changed by substituting alkaline complex for cap. This was done because of the wide variety of commodities found in carbonatites, their variable geophysical expression, and little use, yet, of geophysics in exploration for the specific deposits. The principal use of geophysics in this case has been in definition of the entire alkaline complex and some individual lithologies rather than in deposit definition.

Because of difficulties in fitting the specific physical properties measured by remote sensing methods into the physical properties listing of heading E, and the way that remote sensing methods are applied to minerals deposit exploration and assessment, a separate division, F, was created for this group of geophysical techniques. Under the remote sensing division, descriptions of characteristic features are given.

Following the above headings detailing the geophysical attributes of the deposit type is a heading for comments (G). In heading G the compiler gives general comments about the deposit, attributes that do not fit into other headings, and suggestions.

A list of references (heading H) follows that may include cited and uncited references. This list is not exhaustive. However, it contains many of the more comprehensive and significant references. An effort was made to include references to a wide variety of geophysical methods. In many cases compilers made a literature search of the American Geological Institute’s GeoRef data base CD-ROM (DeFelice, 1991) particularly to identify foreign language literature, and to find quantitative physical property data. The reference lists are intended to provide a firm basis for those wishing to further review the geophysical literature on a particular deposit type.

The final heading (I) presents a few selected geophysical maps, or profiles, or cartoons from the literature illustrating typical responses for the deposit type. These have been redrafted from the originals for clarity.

GEOPHYSICAL METHODS

In this section a very brief review of the various geophysical methods mentioned in the models is given. This review indicates typical applications or problems that each technique can address, and points out some limitations in minerals assessment and exploration. Details of each geophysical technique cannot be given; these are adequately covered in standard texts. However, most English texts provide few practical examples or clues as to what techniques are most applicable to various types of mineral deposits. Texts that partially address these concerns are Van Blaricom (1980) published by the Northwest Mining Association, Kuzvart and Böhmes (1986) who provide an eastern

European view, and the older encyclopedia texts of Heiland (1940) and Jakosky (1950) both of which have sections devoted to geophysical methods in mining worth occasional review. Present day geophysical journals provide limited help, devoting most pages to techniques or theory, and few to case histories.

Although limited to precious metal exploration in Nevada, USA, Corbett (1991) gives an excellent overview of geophysical methods currently being used, and addresses costs and survey design. He notes the need for a geologic model of what is sought, and need for more physical property information so that the geophysicist may better determine if the target is detectable. The models presented in this paper are a start at meeting the needs of the exploration geophysicist as given in the article by Corbett.

Table 1 is a chart showing the various geophysical methods for each of which the physical property, measured parameters, anomaly source and depth of investigation are given, along with examples of application in direct and indirect minerals exploration. This is an adaptation of a chart compiled by Companie General de Geophysique, Massy, France and published with modification by Van Blaricom (1980). The table also shows whether the method may be used in airborne, ground or borehole applications and the relative importance of each of these applications for minerals exploration.

The left half of the chart relates to the physical principles and geophysical aspects of each method, and identifies the basic causes of the possible geophysical anomalies. If an ore deposit does not provide, directly or indirectly, a measurable property (generally a change in a physical property between host rock and ore body) then geophysics will be of no help. Depth of burial by cover rocks is also extremely important in assessing the potential for geophysical methods to identify favorable lithologies, host structures, or the deposit itself. As anomaly sources are buried deeper, their response decreases in amplitude and their spatial wavelength increases until at some point they disappear into the geologic noise. The physical properties of cover, host rock, and deposits provided in this compilation permit modeling so that the user may estimate the possibility of detection for various deposit types of varying depth.

Some geophysical methods, such as gamma-ray and remote sensing measure only surface attributes, and others such as thermal, and some electrical are limited to relatively shallow measurements. While this is a restriction, it does not necessarily imply that these methods are useless for deeper deposits. Secondary and subtle effects, as from geochemical haloes, can often be identified by these methods as indirect measures of the presence of mineralization or structures.

The right half of Table 1 shows applications to minerals exploration both for direct detection, and for indirect detection. For each geophysical method examples are cited from the literature. This table provides an *overview* of the way that geophysical methods can be applied to minerals assessment and exploration and a feeling for the type of contribution to be made by each technique. Comments on each of the methods follow.

<u>Gravity</u>

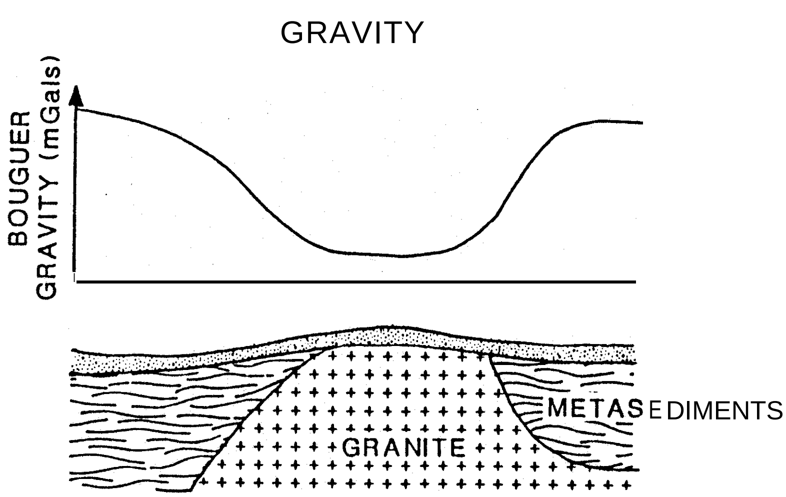


Table 1

	GEOPHYSICAL METHOD					APPLICATIONS TO MINERAL COMMODITIES			
A=airborne, B=borehole, G=ground	Physical Parameter measured	Typical units	Relevant physical property	Typical source of anomaly	Depth of investigation	Direct detection	Example	Indirect detection	Example
1. Gravity G,B,A	Total attraction of earth's gravity field (essentially the vertical attraction of anomalous masses) —— gradient of earth's gravity field	Milligals or gravity unit (0.1 mGal) —— Eōtvōs unit (10^{-9} gal/cm)	density	contrast in rock density	all	deposits of dense ores low density evaporite diapirs	chromite, Cuba Davis et al., (1957) Massive sulfides Portugal Richard et al. (1984) salt domes Peters and Dugan (1949)	gold in volcanics bauxite in karst cavities niobium in alkaline ring complexes sulfur in caprock	U.S.A., Kleinkopf et al. (1970) USSR, Babayants et al. (1970) Canada Gold et al. (1966) U.S.A. Nettleton (1956)
2. Magnetic A,G,B	vertical, or other vector component, or total attraction of earth's magnetic field —— gradient of earth's magnetic field	nanotesla, or gammas —— nanotesla/m	magnetic susceptibility and remanent magnetization "	contrast in magnetic susceptibility; or remanent magnetization, or both "	Surface to Curie isotherm	magnetite ore banded iron formation	Peru, Gay (1966) Canada, Gaucher (1965) Mauritania, Gross and Strangway (1966)	Gold bearing Paleoplacers chromite diamond-bearing kimberlites base metals related to banded-iron formation	S. Africa, Roux (1970 Turkey, Yungul (1956) Gerryts (1967) S. Africa, Campbell and Mason (1979)

Table 1 (continued)

3. Gamma-ray a. scintillometry G,A,B	rate of gamma-ray photons received	counts per second	total quantity of K+U+Th and daughters or	contrast in total K+U+Th in upper 50 cm of earth	upper 50 cm	Uranium	Australia, Montgomery (1972)	Apatite geologic mapping	Brazil, Barreto (1974) U.S.A., Pitkin (1968)
b. spectrometry A,G,B	rate of gamma-ray photons received and their energy	counts per second in various energy bands. If calibrated then %K, and PPM equivalent U and Th	quantity of K,U,Th and daughters	contrasts in K,U, and Th contents in upper 50 cm of earth		Uranium, Thorium "	Greenland, Løvborg et al. (1972) Australia, Tipper and Lawrence (1972)	tin gold greenstone belt mapping	Australia, Webster (1984) various countries Hoover & Pierce (1990) Brazil, Pires and Harthill (1989)
4. Seismic a. refraction G,B	source-receiver position and travel time of seismic energy	meters, milliseconds	Velocity of P or S waves	contrasts in layer velocities or presence of structures	all	Low velocity massive sulfides	U.S.A., Elliot (1967)	uranium lithologic mapping related to sulfides	U.S.A., Pakiser and Black (1957) USSR Vostretsov (1968)
b. reflection G,B	"	"	"	Presence of structures or velocity variations		coal	Ziolkowski (1979)	tin placers geologic province definition	Indonesia Singh (1984) Germany, Trappe et al. (1988)

Table 1 (continued)

5. Thermal a. bore-hole or (shallow hole)	thermal gradient or temperature	degrees C/m degrees C	thermal conductivity	varying heat flux or contrast in thermal conductivity	that of hole	pyrite Uranium	USSR, Lakhtionov (1968) Australia, Houseman et al. (1989)	geologic province definition	USSR, Neprinerov et al. (1989)
b. remote sensing	surface temperature day and night	degrees C	thermal inertia	contrast in thermal inertia	on order of 5 cm			silicic alteration gold district	U.S.A., Watson et al. (1990)
6. Electrical (see comments in text) a. Self potential G,B	natural DC field	millivolts	Eh/pH nd presence of electronic conductor; streaming potential coef.; Thermal coupling coef	vertical change in Eh/pH with presence of electronic conductor; groundwater flow; thermal flux	that of source	massive sulfides Cu, pyrite veins	India, Sengupta et al. (1969) Japan, Yamada (1967)		
b. mise-a-la-masse G,B	applied DC or low frequency AC field	millivolts	resistivity	presence of conductive ore body	that of conductive body	massive sulfide	Cu-Zn-Ag, Canada, Reed (1979	conductive phyllite containing Cu sulfides	Finland, Ketola (1979)

Table 1 (continued)

c. galvanic resistivity G,B	electrode position, applied current, and electric field	meter, amps, millivolts	resistivity	lateral or vertical contrast in resistivity	in practice to about 2 km	massive sulfide	Cu, India, Sengupta et al. (1969)	silicified zone, Au deposit lithologic structure, and alteration mapping of polymetallic replacement deposit	U.S.A., Ehni (1991) U.S.A., Keller et al. (1975)
d. induced polarization G,B	change of resistivity with frequency (PFE) or Phase angle between transmitted and received signal(ϕ) or normalized area of part of received voltage decay curve (chargeability M)	% change milliradians milliseconds	interface ionic polarization phenomena	presence of metallic luster minerals within pore space, presence of surface active clay and zeolite minerals	in practice to about 2 km	disseminated sulfides replacement Zn-Pb karst bauxite	Canada, Hansen and Bass (1966) Albania, Langore et al. (1989) Canada, Lajoie and Klein (1979) Yugoslavia, Sumi (1965)		

Table 1 (continued)

e. electromagnetic methods (see text for comments) G,A,B many variations available	dependent on method	dependent on method	resistivity	changes in earth resistivity	dependent on method; may be restricted to shallow exploration i.e., VLF, or go to mantle depths i.e., MT	massive sulfides airborne magnetite mapping	Canada, Telford and Becker (1979) Canada, Fraser (1981)	alteration, lithology, and structure mapping Au deposit Kimberlite mapping	New Zealand, Wilds and MacInnes (1991) various locals, Gerryts (1967)
f. optical range remote sensing imaging	intensity of reflected light (UV, VIS, IR)	normally recorded as optical or digital intensity image	spectral reflectance, Albedo	changes in spectral reflectance and Albedo	surface only			Au-quartz veins in shear zones uranium alteration in Goldfield District	Australia, Longman (1984) U.S.A., Vincent (1977) U.S.A., Rowan et al. (1977)

The gravity method has been used in exploration for nearly 80 years and makes use of gravity anomalies computed from gravity measurements. In current exploration practice, these measurements usually are made by using ground-based gravimeters that measure variations in the gravity field from one point to another but with amazing accuracy and precision. The gravimeter is not an absolute instrument, but is the only geophysical instrument--and one of the few instruments known to science--that can measure a change in a targeted quantity to about one part in a billion. Because the gravitational effects of shallow bodies targeted in exploration are orders of magnitude smaller than the gravitational effect of the mass of the earth (that also defines the "vertical" direction), it is essentially the "vertical" component of the anomalous mass that is measured. For subsurface exploration, special types of gravimeters are used in boreholes to measure underground densities over a larger volume and with more accuracy than other borehole density-sensing devices.

In exploration of an earlier time, pendulums that measured the absolute value of gravity and Eotvos torsion balances that measured the horizontal gradients of gravity were used, more commonly in searches for hydrocarbons than those for minerals. More recently, special types of commercially developed gravimeters, a gravity gradiometer developed by the Department of Defense, and an experimental gyrostabilized array of accelerometers developed jointly by the Charles Stark Draper Laboratory and U.S. Geological Survey are being evaluated. The last being a technique for extracting vector gravity information in contrast to the non-directional scalar information obtained by all other measuring devices. While the only airborne systems that are commercially available use gravimeters, these systems are used primarily by oil and mineral companies for regional exploration over areas that are relatively inaccessible.

The gravity anomalies used in exploration are computed by subtracting from the measured local field an assumed regional field predicted on the basis of previously assigned densities and geometrical factors for the earth and its topography. It is fortunate that this subtraction process also eliminates the earth-rotation part of the measured gravity, because the resulting gravitational part can be used directly to correlate anomaly with the density of the body that causes it. These gravity (now simply gravitational) anomalies are highs--relatively positive--over shallow bodies that are high in density but are lows--relatively negative--over shallow bodies that are low in density. Thus, high-density bodies of chromite, hematite, and barite generate gravity highs but low-density bodies of halite, weathered kimberlite, and diatomaceous earth generate gravity lows. Apart from these correlations, the gravity method offers another feature unique to it and of exceptional value in prospecting--namely, the capability of predicting the total anomalous mass that causes a given anomaly by analysis only of the anomaly itself. This capability, beyond offering estimates of ore tonnages, translates into predictions of ore volume, given estimates of ore density. It may be noted that, while the gravity method (and magnetic method--to be discussed in the following section) detect only lateral contrasts of physical property (density or magnetization), electrical methods also detect vertical contrasts of physical property (resistivity or conductivity).

The gravity method is generally used in an indirect detection mode for identification of structures or lithologies controlling ore deposition. However, the method is applicable to direct exploration for very high or low density ores such as chromite or halite. In some cases it can be effectively used to provide a measure of overburden thickness. In other cases, where the size of the ore body and its density contrast with the host are sufficiently large, gravity methods can provide a better estimate of reserves than limited drilling.

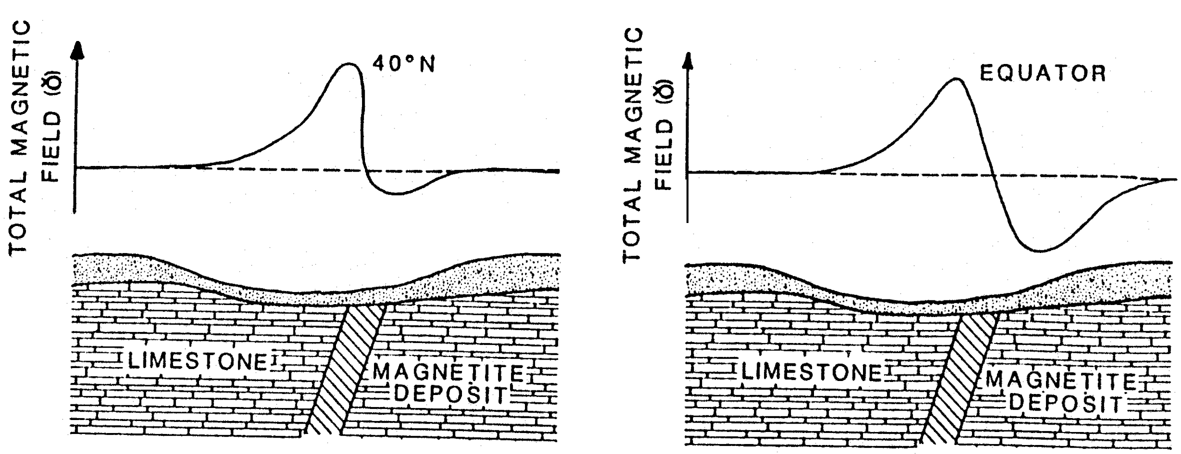
Direct detection of ore by gravity methods is well illustrated by the work of Yungul (1956) in Turkey, and Davis and others (1957) in Cuba in the exploration for podiform chromite. Yungul presented a series of curves that define the maximum magnitude of the anomaly to be expected as a function of deposit size and depth of burial. Using grade-tonnage data from Cox and Singer (1986), we note that the complete range of values to be expected for an economic deposit may be calculated in a similar way. Figure 1 presents an example for major podiform chromite deposits using grade-tonnage data of Singer and others, 1986. Following Yungul, a spherical chromite body is assumed with a density of 4.0 gm/cm^3. Host density is assumed at 2.67 gm/cm^3, a little larger than Yungul used. Three curves are shown on figure 1 giving the maximum value of the gravity anomaly for deposits of 0.0022 million tonnes, 0.02M tonnes and 0.2M tonnes. These values represent the 10th, 50th, and 90th percentiles of known deposit sizes. The area bounded by the 0.0022 and 0.2M tonne curves, the line defining the top of the spherical ore body at the surface, and a horizontal line representing geologic noise gives the range of maximum gravity anomalies as a function of depth of burial to be expected for this type of deposit. Figure 1 clearly shows that geologic noise needs to be minimal if the smaller economic bodies are to be found.

These curves are dependent on the density contrast between host and the chromite ore which can vary due to uncertainties in both host and ore densities. From much of the published literature a density of 4.0 gm/cm^3 appears reasonable for chromite (for example Mironov 1972) but measurements by Segalovich (Solovov and others, 1970) on 565 samples of podiform chromite from the Kempirsoi massif, Kazakhstan give a median density of 3.57 gm/cm^3. A density as low as this would significantly affect the detectability of chromite bodies from that shown in figure 1. This surves to emphasize the need for caution when using average rock property values from published compilations.

Figure 2 is a similar illustration, but for karst bauxite deposits. Again the body is assumed spherical but with a density of 2.45 gm/cm^3, and in a 2.55 gm/cm^3 host, an average value for limestone. From Mosier (1986) the 10th, 50th and 90th percentile of deposit sizes are 3.lM, 23M, and 170M tonnes. The maximum gravity anomaly for the karst bauxite model is seen to be slightly less than that for major podiform chromite deposits, even though the sizes of bauxite deposits are much larger. This again points out the difficulty of identifying the smaller bauxite deposits with gravity methods.

<u>Magnetic</u>

MAGNETIC



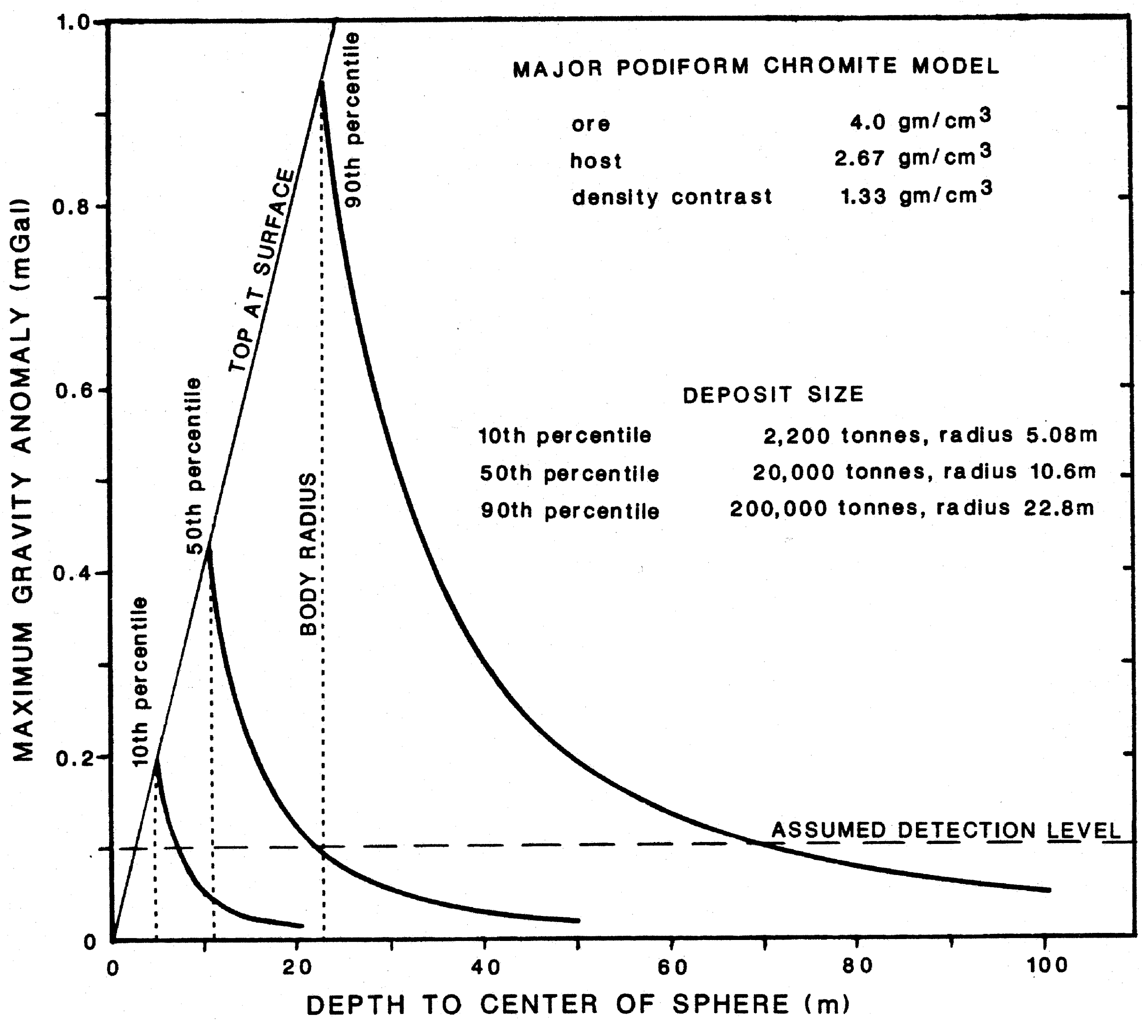


Figure 1. Graph showing the maximum gravity anomaly due to a spherical body of chromite, 4.0 grams per cubic centimeter in a 2.67 grams per cubic centimeter host as a function of depth of burial for bodies of 0.0022 M, 0.02M, and 0.2M tonnes. Size range of ore bodies represent the 10th 50th, and 90th percentiles of major podiform chromite deposits from Singer and others (1986).

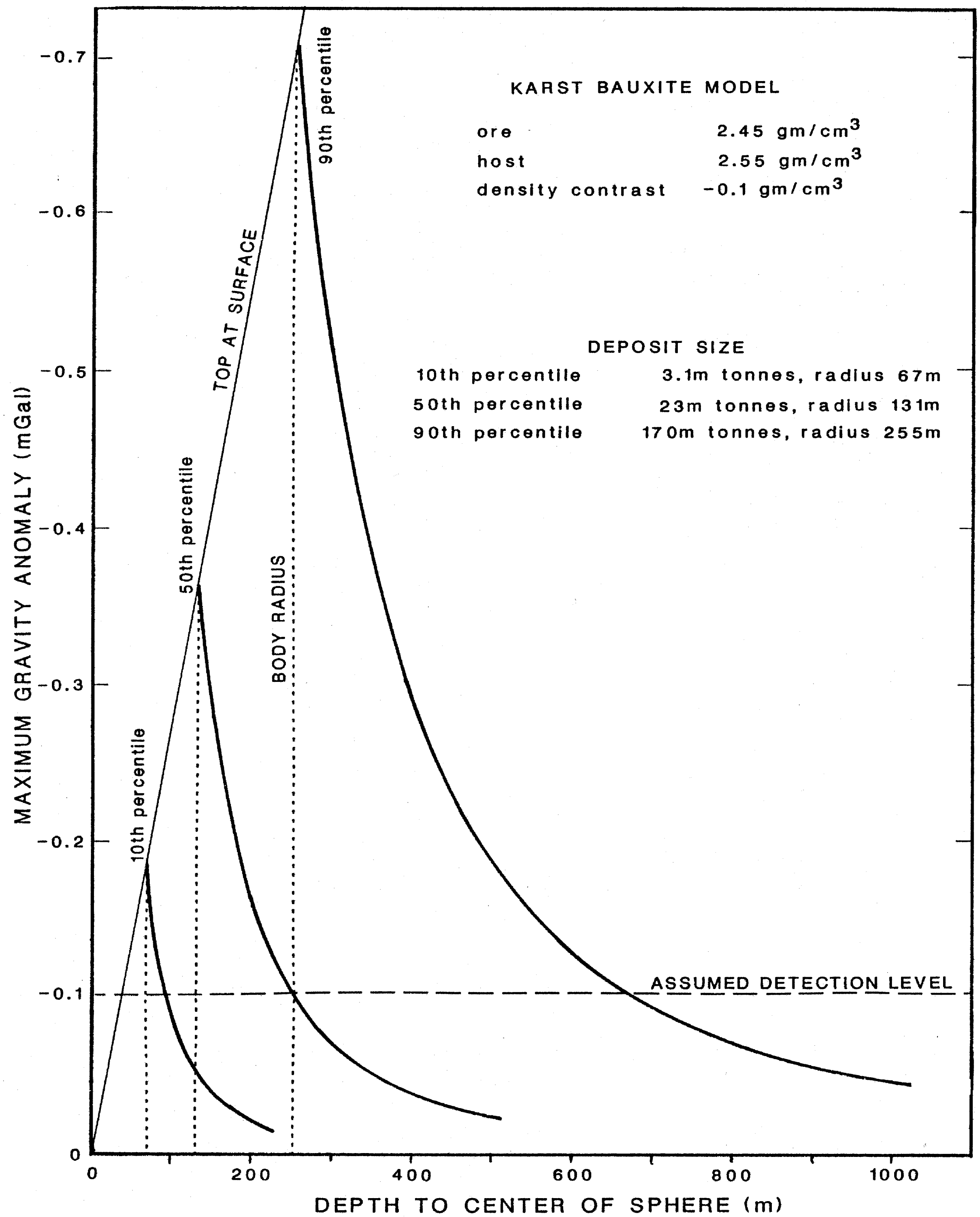


Figure 2. Graph showing the maximum gravity anomaly due to a spherical body of bauxite, 2.45 grams per cubic centimeter in a 2.55 grams per cubic centimeter host as a function of depth of burial for bodies of 31M, 23M, and 170M tonnes. Size range of ore bodies represent the 10th, 50th and 90th percentiles of karst bauxite deposits from Mosier (1986).

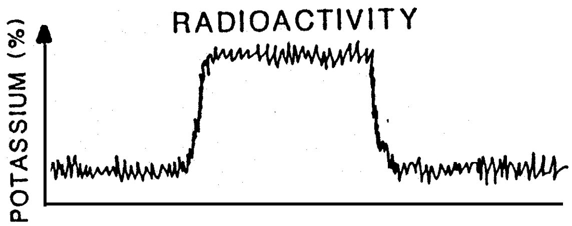
The magnetic method has been in use for more than one hundred years and makes use of magnetic anomalies computed from magnetic measurements. Although exploration programs included measurements made by using dip-needles and vertical or horizontal magnetic balances prior to about 1950, more recent programs almost exclusively restrict measurements made by using fluxgate, proton-precession, Overhauser, and optical absorption magnetometers. Normally total-field data are acquired; occasionally, vector measurements are made.

At exploration depths it is the presence of magnetic iron oxide (magnetite), iron-titanium oxides (titanomagnetite, titanomaghemite, and titanohematite), and iron sulfides (pyrrhotite and greigite) containing various combinations of induced and remanent magnetization (which added together vectorially comprise the total magnetization) that perturb the earth’s primary field (Reynolds and others, 1990). The magnitudes of both induced and remanent magnetization depend on the quantity, composition, and size of the magnetic-mineral grains. The induced magnetization, which is the product of the magnetic susceptibility and the earth’s ambient field, can be expressed by the magnetic susceptibility because the ambient field is relatively constant in magnitude and direction. The direction of induced magnetization approximately coincides with the direction of the ambient field, except for bodies exhibiting a strong anisotropy of magnetic susceptibility, such as magnetite and iron formation. The magnitude and direction of remanence further depends strongly on the various physico-chemical environments and various directions, polarities, and strengths of magnetic fields to which magnetic minerals have been subjected during their existence. A particularly striking contrast between induced and remanent magnetization relates to magnetic-mineral grain size: In general, relatively small grains exhibit a small susceptibility, and thus a weak induced magnetization, whereas they produce a relatively strong and stable remanent magnetization. While large grains usually exhibit a large magnetic susceptibility, and thus strong induced magnetization, they may produce either a weak or strong remanent magnetization. The relationship between the two kinds of magnetization is often expressed by the Koenigsberger ratio of remanent magnetization magnitude to induced magnetization magnitude. It should be noted that induced magnetization can profoundly affect the results of some electromagnetic measurements over electrically conductive, magnetite-rich bodies, especially those measurements made by using a controlled source in the frequency domain, as discussed in a later section.

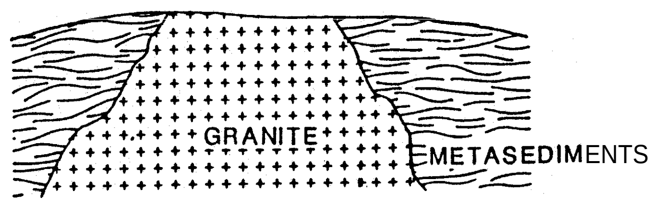
In contrast to gravity anomalies, which occur directly over their sources, magnetic anomalies usually are shifted or displaced laterally relative to their sources, depending upon magnetization direction. Fortunately, it is often possible to re-position magnetic anomalies directly over their sources by judicious application of filtering techniques.

Magnetic anomalies also may be associated with alteration of magnetic minerals in rocks that host ore deposits related to hydrothermal systems (Hanna, 1969; Criss and Champion, 1984) and thus may outline zones of fossil hydrothermal activity. Because the rock alteration can effect a change in bulk density as well as magnetization, the magnetic anomalies, when corrected for magnetization direction, sometimes coincide with gravity anomalies. This association of a contrast of both magnetization and density in a homogeneous body implies an association of magnetic and gravitational anomalies that is expressed by Poisson’s relation. In exploration geophysics Poisson’s relation may be used to predict the ratio of magnetization magnitude to density, given the corresponding magnetic and gravity anomalies; further, if either magnetization or density is already known, the other can be computed. Especially interesting to explorationists is the occasional “coupling” of magnetic highs to gravity lows; this “coupling” is sometimes observed over relatively highly magnetic, low-density glassy volcanic rocks containing single-domain magnetic-mineral grains; highly vesicular basalt; serpentinite and weathered kimberlite; and felsic-to-intermediate plutons emplaced into relatively nonmagnetic gneissic terrain.

Although direct magnetic exploration is essentially limited to iron ore deposits such as those of magnetite or banded iron formation, magnetic methods often are an essential tool for deducing subsurface lithology and structure. These methods also may be used for placer identification by mapping of magnetite concentration, exploration for chromite due to associated magnetite, base-metal exploration by identification of associated magnetite or pyrrhotite content, and identification of zones favorable for deposition on regional or district scales.



Gamma-ray methods



Gamma-ray methods may use scintillometry to identify, indiscriminately, the presence of the radioelements potassium (K), uranium (U) and thorium (Th), or by the use of multi-channel spectrometers provide qualitative or quantitative measures of the individual radioelements. Spectrometers may be calibrated to give quantitative measures of radioelement concentrations if readings are made over test areas of known concentrations. It is unfortunate that many published gamma-ray data were obtained without the use of calibrated systems.

Gamma-ray methods have had wide application in uranium exploration because they provide direct detection. However, until recently in the West, these methods have not had as much application to other commodities as the authors believe they deserve. The former Soviet Union appears to have made the most use of this technique (for example see Hoover and Pierce, 1990 or Vavilin and others, 1982) in minerals exploration. For those looking at applications, the Russian literature needs to be examined.

When looking at uranium or thorium values derived from gamma-ray spectrometry the user needs to remember that the values are expressed in equivalent uranium or thorium content based on equilibrium of the decay series. This condition is often not met by uranium in the near surface (Durrance, 1986), because of uranium's mobility in an oxidizing environment. However, it may be relatively immobile in near surface units high in phosphates, clay, or organic materials.

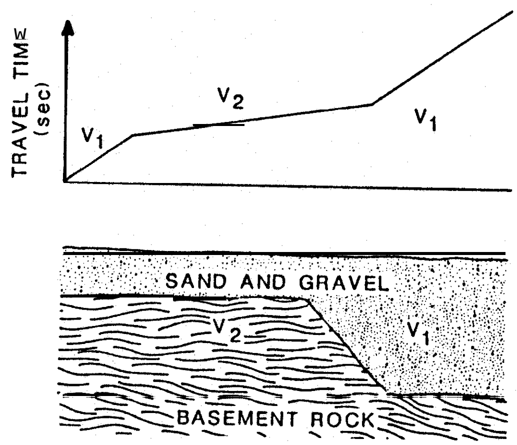
Thorium is generally the most immobile of the three radioelements, behaving geochemically in a way similar to zirconium. It is often found in association with the rare earths. Thorium content, like uranium content, tends to increase in felsic rocks and generally increase with alkalinity. The

K/Th ratio in igneous rocks is generally on the order of 3 x 10^3, and the Th/U ratio typically 3.5 to 4,0 (Durrance 1986).

Radon and radiogenic helium soil gas methods are used more often by the geochemist than by the geophysicist. They will not, therefore, be considered to a major extent in the compilation.

Indirect applications of gamma-ray methods include exploration for coal and lignite, radioactive heavy minerals, and phosphates. The identifiacation of lithologic differentiation in igneous bodies, and identification of radioelement haloes, primarily potassium, around hydrothermal ore deposits are other important uses. Hansen (1980) provides an excellent review of gamma-ray methods for the explorationist.

SEISMIC



Seismic methods

Seismic techniques have had relatively little use in minerals assessment and exploration at the deposit scale, in part due to their relatively high cost. However, they can provide better structural detail and better estimates of depth to lithologies of differing acoustic impedance than other geophysical techniques. The refraction method is most used in minerals work principally for mapping of low-velocity alluvial deposits such as those of gold, tin, or sand and gravel. The more expensive reflection method is not commonly used except for exploration for salt domes. However, most of the salt dome exploration is for associated petroleum and not for the salt or sulfur content of the dome. The reflection method is also used for offshore placer exploration where data acquisition becomes less expensive.

In this compilation only controlled-source (active) seismic techniques are considered. Large scale regional studies such as used by the Russians for regionalization of metallogenic districts may make use of both active and passive seismic (earthquake, or microseismic sources) methods. Because of difficulties in evaluating these regional data, and assigning characteristics to particular model types passive seismic methods are not generally considered in this preliminary model compilation.

Thermal methods

Two quite distinct techniques are included under thermal methods on table 1. Under (a) are the borehole *or* shallow probe methods for measuring thermal gradient, which with a knowledge of the thermal conductivity provides a measure of heat flow. These are essentially in-hole techniques. The second technique (b) is an airborne or satellite based method, one in which the earth's surface temperature is determined by measuring the thermal infrared radiation emitted by the surface. By measuring day and night temperatures the thermal inertia of the surficial materials may be calculated.

Borehole thermal methods have direct application to geothermal resources, but are seldom used in minerals exploration. However, there appears to be some potential for this method in exploration. Sources of heat that can produce heat flux anomalies relevant to minerals exploration are oxidizing sulfides, and high concentrations of radioelements. On the regional scale, Brown and others (1980) have shown a correlation between high heat flow provinces and mineralization in Northern-Central England and Southwest England. They suggest that heat production due to radioelements in the Hercynian and post-Hercynian granites was responsible for generating hydrothermal systems long after the granites had cooled, and that these late hydrothermal systems then produced the numerous epithermal mineral deposits of the region. Ovnatanov and Tamrazyan (1970) and Neprimerov and others (1989) also comment on the applicability of thermal methods for identifying structures on a regional scale.

On the deposit scale, a number of papers indicate the potential for thermal studies. High heat flow has been observed over the Olympic Dam Cu-U-Au deposit, Australia (Houseman and others, 1989); over a carbonatite in Nebraska (Gosnold and others, 1981); and over a small mineralized Tertiary intrusive in New Mexico (Zielinski and DeCoursey, 1983). Temperature anomalies over sulfide bodies of about $1^{\circ}c$ are shown in Lakhtionov (1968) who notes that thermal methods have been used in Russia since 1935. Bose (1983) notes its increased use in India where 2 to $5^{\circ}c$ anomalies over sulfide bodies are used to help discriminate ore from graphite, but no details are given. Logn and Evensen (1973), based on measurements of thermal conductivity on ore and county rock from the Joma pyrite deposit, also suggest the possibility of thermal measurements to distinguish between sulfide ores and graphite.

Structures such as salt domes, basement highs, sand lenses, and faults also can be identified by thermal methods (Van Ostrand, 1934; van den Bouwhuijsen, 1934; Jakosky, 1950; Ovnatanov and Tamrazyan, 1970). Where boreholes are available, particularly in covered terrain, the explorationist needs to be aware of the potential for thermal methods.

Thermal infrared imaging methods belong to the broader remote sensing techniques. Images obtained in this wavelength range may be used as other photographic or digital images for photogeologic type interpretation or, if day and night images are available, further processed to provide an image of the thermal inertia of the surface. Unconsolidated or glassy materials can be distinguished by their low thermal inertia. This airborne method can also distinguish limestone from dolomite for lithologic mapping.

Electrical methods

In contrast to other geophysical methods, electrical methods comprise a multiplicity of separate techniques that measure distinct geophysical attributes of the earth, with differing instruments and procedures, having variable exploration depth and lateral resolution, and with a large and confusing list of names and acronyms describing techniques and variants of techniques. We have divided the electrical methods into five distinct classes: (A) the self potential, (B) the induced polarization method, (C) the mise-a-la-masse, (D) the galvanic resistivity, and (E) the electromagnetic resistivity. These are shown in Figure 3, where the three distinct source phenomena are identified, and some variations of each method listed. In the

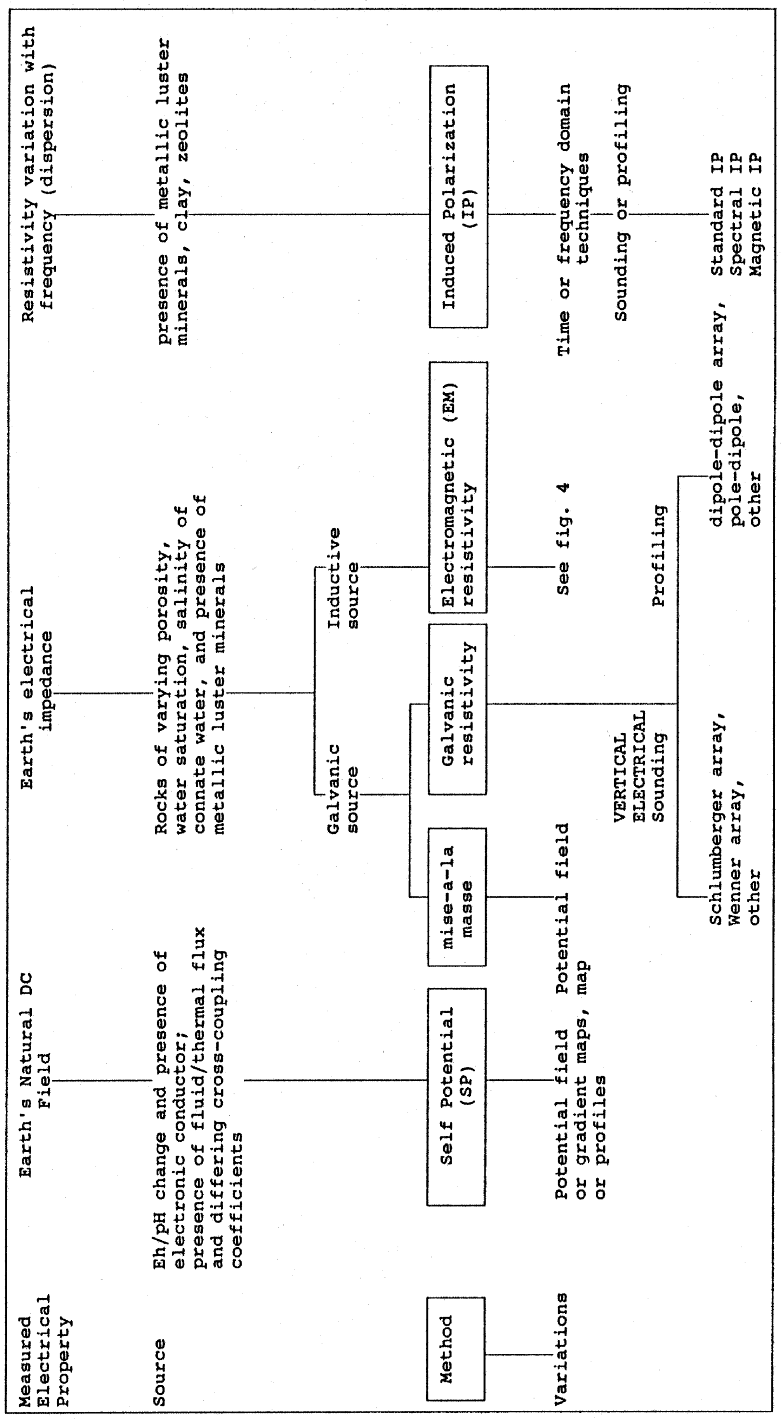
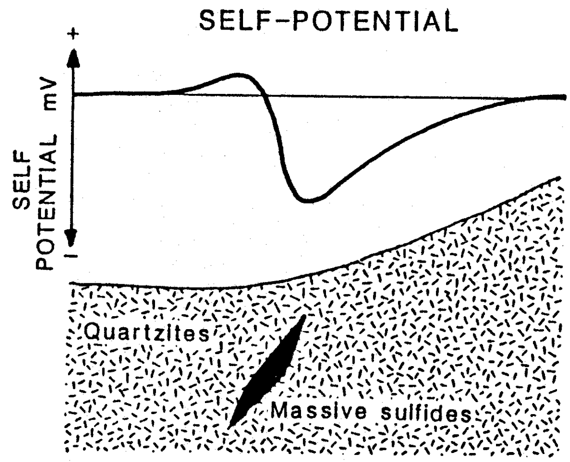


Figure 3. Diagram showing the five principal electrical methods and their source phenomena.

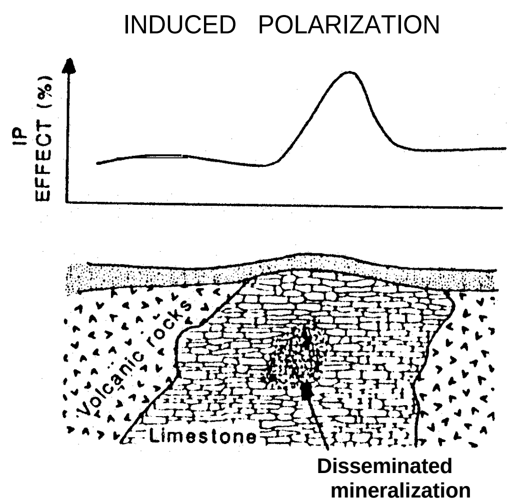
case of electromagnetic methods there are so many variations, and differing acronyms and trade names that the variations are detailed in Figure 4. In spite of all the variants of the electromagnetic method, measurements fundamentally are of the earth's electrical impedance or relates to changes in impedance. Some of the electromagnetic methods listed in figure 4 are really hybrid techniques because source fields may be generated through galvanic contact to the earth (TURAIR, CSAMT, etc.), or receiver electric fields may be measured through galvanic contact to the earth (CSAMT, AMT-MT, VLF, telluric, etc.). However, for convenience these have been classified with the electromagnetic methods.

A. Self Potential

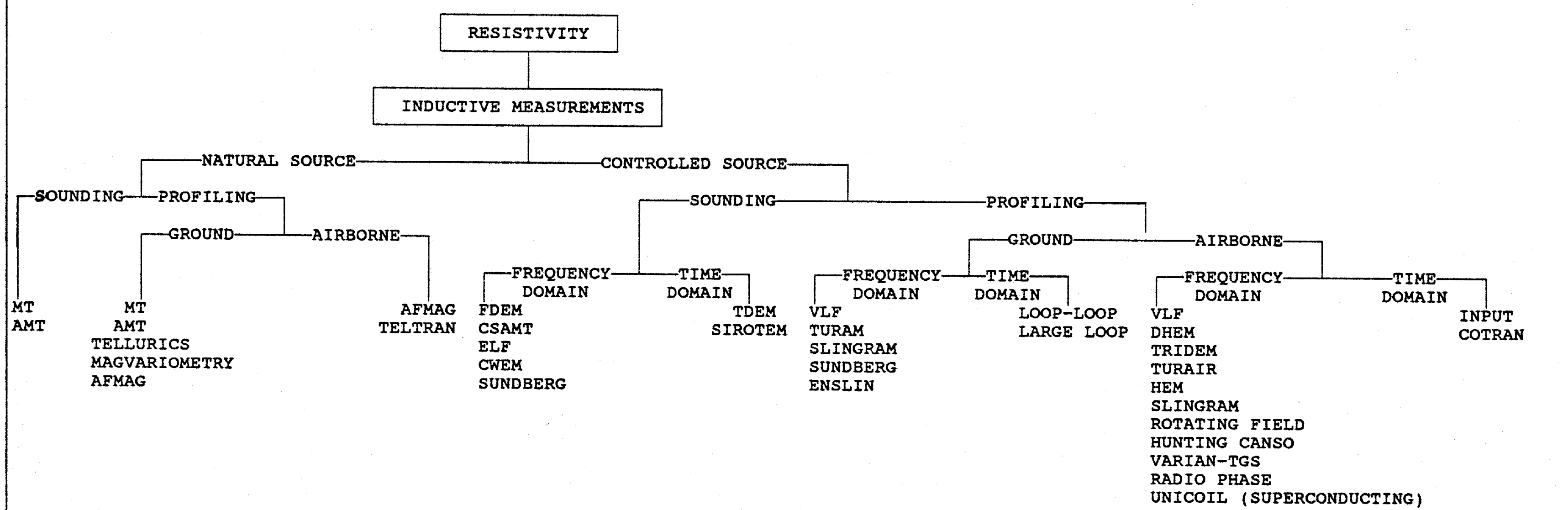


For the self potential method there are several possible sources giving *rise* to a dc or quasi-dc. natural electrical field. For mineral deposits the most important is the Sato and Mooney (1960) type source established when an electronic conductor, such as a massive sulfide or graphite body, extends between an oxidizing and reducing zone or over a range in pH. Other self potential sources are due to fluxes of water or heat through the earth.

B. Induced polarization



The induced polarization method provides a measure of polarizable minerals within the water bearing pore spaces of rocks. These minerals are



AFMAG - audio frequency magnetics
AMT - audio-magnetotellurics
CSAMT - controlled source audio-magnetotellurics
DHEM - digital helicopter EM
ELF - extra low frequency
EM - Electromagnetics
FDEM - frequency domain EM

INPUT - integral pulsed time domain EM
MT - magnetotellurics
TDEM - time domain EM
TRIDEM - three loop airborne EM
TURAIR - airborne TURAM
TURAM - two loop EM
VES - vertical electric sounding
VLF - very low frequency

TELTRAN - telluric transient
CWEM - continuous wave EM
TURAIR - airborne TURAM
HEM - helicopter EM
COTRAN - correlation of transients

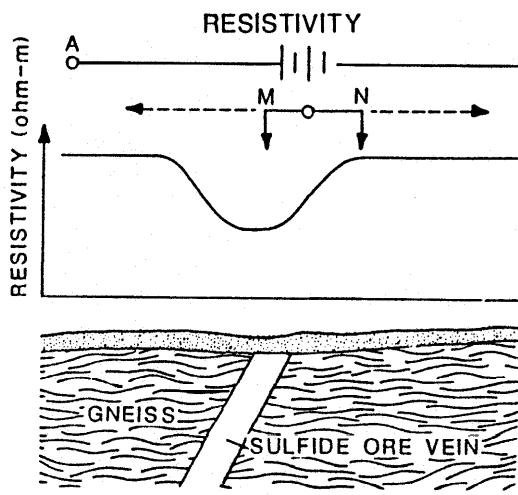
Figure 4. Tree diagram showing a classification of electromagnetic methods, and some of the techniques belonging to each branch.

metallic-luster sulfides, clays, and zeolites. The above mineral groups, in order to be detected, must present an active surface to the water in the pore space. Sulfide mineral grains completely enclosed by a nonconducting matrix such as silica will not be detected by the IP method. Since the IP response relates to the presence of active surface areas within the rock, disseminated sulfides provide a much better target than massive sulfides for this technique. This method has found its greatest application in exploration for disseminated sulfide ores where its good sensitivity (as low as 0.5% total metallic luster sulfide may be detected, according to Sumner, 1976) makes it a primary tool.

C. Mise-a-la-masse

The Mise-a-la-masse method is a little used technique that is applied to conductive ore deposits that have a large resistivity contrast with the host rock. Under these conditions, electrical contact is made to the *ore* body, either at the surface or through a drillhole, with a source of direct or low frequency current. The other electrical pole is placed some distance away. When energized, the ore body becomes essentially an equipotential surface. The field from this body can then be mapped at the surface revealing the position of ore below the surface. An excellent example of this method is given by Mansinha and Mwenifumbo (1983). Application of this method is principally for massive sulfides.

D. Galvanic resistivity

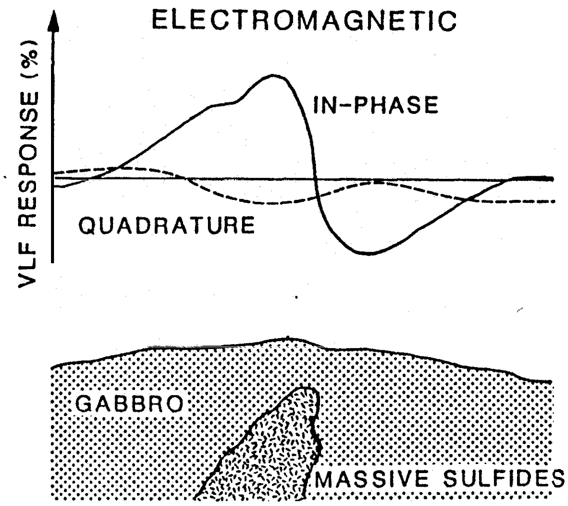


Galvanic resistivity methods, often referred to as "dc" resistivity methods, provide a measure of earth resistivity using a dc or low frequency ac current source. Source current is introduced into the earth, and the electric field is measured, through electrodes in galvanic contact with the earth. Resistivity in earth materials is primarily a function of porosity and water content, high porosity giving low resistivity in water saturated rocks. Resistivity values may range over five orders of magnitude in normal near-surface environments. Electrical conduction in rocks at dc and low frequencies occurs through ionic migration in the water of the pore spaces and more rarely, partially by electronic conduction through metallic luster minerals. Because metallic luster minerals typically do not provide long continuous circuit paths for conduction in the host rock, bulk rock resistivity almost always is controlled by the water content and dissolved ionic species present.

In contrast to potential field methods dealing with natural fields such as gravity, magnetic, and self potential methods, the galvanic resistivity techniques use an applied field and are thus able to control the depth of exploration by the spacing of the current and potential electrodes. If one is looking for lateral resistivity changes within a given depth range, then a fixed electrode array may be used to profile across an area of interest. On the other hand, if information on variations of resistivity with depth are desired, then an array may be expanded about a fixed point (a vertical electrical sounding, VES). The variations between profiling and sounding and between electrode arrays leads to differing names being applied to each variant, i.e., Schlumberger (array), vertical electrical sounding (VES), etc.

The galvanic techniques have application to a wide variety of ore deposit exploration. Massive sulfides can provide a direct very low resistivity target, or alteration products within and around hydrothermal deposits often provide a clear low resistivity target. The wide range of resistivities of earth materials also makes the method applicable to identification of lithologies and structures that may control mineralization.

E. Electromagnetic



Electromagnetic methods are probably the most confusing to the non-practitioner because of the many variants, and acronyms, or trade names used to describe them. Figure 4 presents one scheme for classification of EM methods in a tree form. The first branch is based on whether the energy source is natural or artificial. For each of these the next level of branching is based on whether the method is a profiling technique or a sounding technique. The third level of branching is based on whether it is an airborne or ground method, and the last branch based on time domain or frequency domain techniques. At the ends of these 9 resultant branches are given the names and acronyms of some of the electromagnetic methods that apply. In all, thirty-one different terms are shown, and this is not an exhaustive list.

The practical exploration depth of each system is quite variable and depends on the operating frequencies, the rock resistivity, structure, and the source-to-receiver distance. For controlled source airborne methods the maximum exploration depth is on the order of 100 meters. The naturalsource airborne methods have greater depth potential, but unfortunately none have been used for many years. As in galvanic resistivity techniques, soundings can be made by changing the source-to-receiver separation. In practice such soundings are normally used in shallow exploration. However, electromagnetic methods also permit sounding by variation of the operating frequency or time, for time domain systems, and this procedure is becoming of greater importance in exploration, especially where definition of deep features are desired. In the compilation of deposit characteristics no attempt is made to distinguish among the numerous EM methods, nor in many cases between EM and galvanic resistivity methods. For all of these various techniques, they either provide a measure of resistivity or impedance or respond to changes in resistivity or impedance, and this is the important attribute for the model.

The most common application of EM methods to minerals exploration has probably been in the search for massive sulfides. Normally airborne methods are used to screen large areas providing a multitude of targets for further screening by ground methods. Airborne EM methods are now beginning to find increasing use in mapping applications where lithologic and structural features can be identified in areas of difficult access or where cover exists (Palacky, 1986; Hoover and others, 1991).

Hohmann and Ward (1981) provide an excellent review of electrical methods that are used in minerals exploration.

Remote Sensing

In table 1 the remote sensing category includes only those methods making use of images obtained in the ultra-violet (UV), visible (VIS) and near infrared (IR) bands of the electromagnetic spectrum. Data in this range are treated in image format, often in digital form, so that they can be conveniently processed. Where single images are used, interpretation of lithologies and structures is based on photogeologic methods. However, recent airborne and satellite multispectral digital systems now permit extraction of much more information from the images. By comparison with known spectral responses of minerals or mineral groups, the presence of iron hydroxides, silica, clay alteration, etc., can be defined over broad areas.

In the compilations of deposit models remote sensing attributes from UV to near IR methods are most often mentioned. However, where information is available, the remote sensing category will include thermal IR characteristics and side-looking airborne radar (SLAR).

Other methods

Like SLAR, there are a number of other geophysical or quasi-geophysical methods that have been applied to mineral deposits or have potential application, but have a very limited history particularly in the western literature. Techniques such as the piezoelectric method for quartz veins (Volarovich and Sobolev, 1969), UV laser induced fluorescence to find scheelite, hydrozincite and other fluorescent minerals (the Luminex method Seigel and Robbins, 1983), airborne gas sniffing such as for mercury, the Russian CHIM (partial extraction of metals) electrogeochemical sampling technique, radon caps, etc., are examples. These are not covered in the model compilation in general. If the compiler finds a reference, and feels that one of these uncommon methods is or may be important then it would be mentioned in the comments section of the model.

Ground penetrating radar also is not covered, although it has had some limited applications in mineral exploration. Hammond and Sprenke (1991) identified sulfides below glacial ice, Davis and others (1984) describe its applications for placer exploration, and Annan and others (1988) show its application in determining stratigraphic relationships in potash mining.